



Process based simulation of tree growth and ecosystem services of urban trees under present and future climate conditions

T. Rötzer^{a,*}, M.A. Rahman^b, A. Moser-Reischl^a, S. Pauleit^b, H. Pretzsch^a

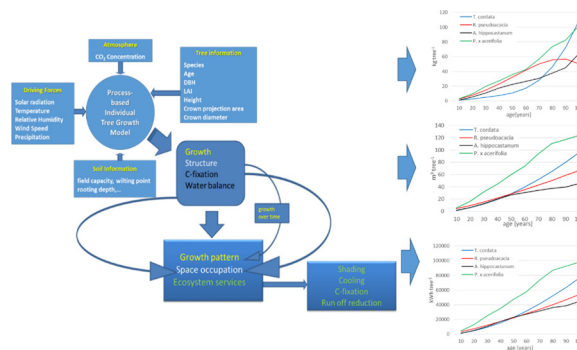
^a Technical University Munich, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany

^b Technical University of Munich, Emil-Ramann-Straße 6, 85354 Freising, Germany

HIGHLIGHTS

- Climate change and increasing urbanization will clearly affect the urban climate.
- Ecosystem services of urban trees can mitigate urban climate changes.
- An urban tree growth model is introduced which is able to simulate these services.
- Growth is calculated process based in dependence on environmental conditions.
- Ecosystem services strongly depend on species, tree age and tree size.

GRAPHICAL ABSTRACT



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ABSTRACT

Global processes of urban growth lead to severe environmental impacts such as temperature increase with an intensification of the urban heat island effect, and hydrological changes with far reaching consequences for plant growth and human health and well-being. Urban trees can help to mitigate the negative effects of climate change by providing ecosystem services such as carbon storage, shading, cooling by transpiration or reduction of rainwater runoff. The extent of each ecosystem service is closely linked with the tree species as well as with a tree's age, size, structure and vitality. To evaluate the ecosystem services of urban trees, the process-based growth model CityTree was developed which is able to estimate not only tree growth but also the species-specific ecosystem services including carbon storage, transpiration and runoff, shading, and cooling by transpiration. The model was parametrized for the species small-leaved lime (*Tilia cordata*), robinia (*Robinia pseudoacacia*), plane (*Platanus × acerifolia*) and horse chestnut (*Aesculus hippocastanum*). The model validation for tree growth (stem diameter increment, coefficient of correlation = 0.76) as well as for the water balance (transpiration, coefficient of correlation = 0.92) seems plausible and realistic. Tree growth and ecosystem services were simulated and analyzed for Central European cities both under current climate conditions and for the future climate scenarios. The simulations revealed that urban trees can significantly improve the urban climate and mitigate climate change effects. The quantity of the improvements depends on tree species and tree size as well as on the specific site conditions. Such simulation scenarios can be a proper basis for planning options to mitigate urban climate changes in individual cities.

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* Corresponding author.

E-mail address: Thomas.roetzer@tum.de (T. Rötzer).

1. Introduction

The urban population will amount to >60% of the global population in the year 2030 and exceed six billion people in 2050 (UN, 2014). This will involve an increased traffic volume (Gong et al., 2012) and more sealed surfaces (Scalenghe and Marsan, 2008). As a result the climate conditions of a city will be modified substantially. Reduced wind (Ossenbrügge and Bechtel, 2010), elevated rainwater discharge along with diminished soil infiltration (Armson et al., 2013; Mejia and Moglen, 2010), lower air humidity (Rötzer, 2007) caused by lower plant transpiration (Kuttler, 2004; Rahman et al., 2017a, 2017b) and changed radiation patterns (Santamouris et al., 2001) will raise the temperature, i.e. intensify the urban heat island (UHI) effect (Oke, 1982; Pongracz et al., 2010). Peng et al. (2011) calculated a daily mean annual UHI of 1.5 ± 1.2 °C across 419 global big cities and Shepherd (2005) found up to 10 °C higher air temperature in cities compared to their neighboring non-urban areas.

In addition to these urban induced climate changes global climate change will further increase the temperature of cities as well as other environmental variables (Coburn, 2009; Gill et al., 2013; Savi et al., 2015). These changes and a predicted increasing number of extreme events (e.g. Easterling et al., 2000; Fischer and Schär, 2010) will have far reaching consequences for plant growth and the provision of ecosystem services ES (e.g. Rötzer et al., 2012; Keenan, 2015; Brune, 2016). This is particularly true for trees as they are long living organisms and account for the larger part of the urban green.

Fang et al. (2014), Kauppi et al. (2014) or Pretzsch et al. (2014) found climate change induced higher growth rates of forests in the course of the last century. A similar pattern, i.e. globally accelerated tree growth was reported by Pretzsch et al. (2017) for urban trees in major cities associated with higher values in urban areas compared to non-urban ones. According to the authors the reasons behind are the synergy between higher temperatures (IPCC, 2014), longer growing periods (Chmielewski and Rötzer, 2001) and higher nutrient inputs (Churkina et al., 2010).

However, the processes, interactions as well as feedforward and feedback reactions within the atmosphere-plant-soil system are hardly understood because analyses mostly concentrate on single ecosystem components (e.g. Bergh et al., 2003; Garcia-Gonzalo et al., 2007; Rötzer et al., 2013) which do not fully represent atmosphere-biosphere-hydrosphere relations (Rebetez and Dobbervin, 2004). Studies of such complex, often nonlinear reaction patterns are challenging, particularly when other processes and cycles (e.g. water or nutrient cycle) are included. A possible way to overcome this challenge is the use of process-based growth models, which include physiological, physical and biochemical reaction processes. In forest science such models are becoming increasingly common. Pretzsch et al. (2014) using a growth model could show that the accelerated growth of Central European forests can only be explained if changing climate over the 20th century is considered along with other global changes (prolonged growing season, increasing N-deposition, atmospheric CO₂-concentration). In case of urban green infrastructure (GI) such models are not existing, particularly for Central Europe. The few existing tree growth models (i-Tree, UFORE, Lindenmayer systems, L-Peach, CityGreen, UrbTree - for an overview see e.g. McPherson and Peper, 2012) are based mainly on empirical approaches, i.e. on statistical equations which are difficult to apply outside the conditions for which they are parametrized. The i-Tree model was developed by using inventory and local meteorological data (Nowak and Crane, 2000; Nowak et al., 2008, 2013). i-TreeEco as part of the i-Tree model suite is based on average growth rates, canopy structures and biomass allometries for different species altered by climate (Nowak et al., 2008). The CityGreen model (Peng et al., 2008) is a GIS-extension calculating tree growth by using constant growth rates depending on a classification of American forests (Longcore et al., 2004). The spatially explicit tree growth model UrbTree (Kramer and Oldengarm, 2010) uses aerial images to

predict individual tree growth by a spatial analysis of the surrounding environment.

For a sustainable planning of GI of cities (Pauleit et al., 2017), information about biomass and volume growth and about the dimensional changes of urban trees is needed. Furthermore, GI of cities also provide ES. They are defined as “benefits people receive from an ecosystem” (Leemans and De Groot, 2003; MA, 2005). Key regulating ES offered by GI are carbon fixation, shading, cooling by transpiration and runoff reduction. Although the carbon stock of the urban green is smaller compared to natural forests, the storage capacity is considerable (Moser et al., 2017). Nowak and Crane (2002) for example calculated a carbon fixation amount of 1.3 Mio. tC for New York city. Hereby, trees are the main contributors with over 97% (Davies et al., 2011). Through transpiration and interception, trees also regulate the water flow and can mitigate runoff (Villarreal and Bengtsson, 2005; Pataki et al., 2011a), whereby tree species and structure play an essential role (Xiao et al., 2000; Bayer et al., 2018; Rahman et al., 2019a). Through shading and transpirational cooling of trees the ambient air temperature can be reduced (Kong et al., 2017). Such mitigations of the UHI effect by GI was found both at the macro- and microscale (Edmondson et al., 2016; Rahman et al., 2011; Zölch et al., 2016).

Thus, a sustainable management of GI, especially of a city's tree population can help to mitigate negative impacts of climate change. This requires precise information on growth rates, dimensional changes and ES of the most common urban tree species depending on age and on the environmental conditions. A process-based, climate sensitive growth model which is able to simulate the development of trees as well as their ES under differing present and future climate conditions can be a first step to face these challenges.

Therefore, the research questions of this study are: (i) Can urban tree growth and ES be simulated based on site specific environmental conditions? (ii) Is it possible to quantify ES of urban trees such as carbon fixation, water consumption (=transpiration), shading, cooling by transpiration, or runoff reduction for Central European cities by a process based growth model? (iii) How do tree growth and ES of Central European cities change under predicted future climate conditions?

2. Material and methods

2.1. Description of the urban tree growth model CityTree

A process-based model for individual trees was developed to assess the influence of a changing climate, changing soil characteristics and/or changing ambient conditions as well as the influence of extreme events on growth, productivity and ES of urban trees (Fig. 1). Along with the age and the tree species, easy to measure data on tree dimension (diameter at breast height dbh, tree height h, crown length cl and crown diameter cd) form the initial values to start the growth simulation. The soil type is characterized by its field capacity, permanent wilting point and rooting depth. The percentage of soil sealing is needed to describe the infiltration of water into the soil. In addition to the CO₂-concentration of the atmosphere monthly climate data are used as driving forces of growth.

The model is comprised of eight modules (Fig. 1) and is parameterised for the following tree species: small-leaved lime (*Tilia cordata*), robinia (*Robinia pseudoacacia*), plane (*Platanus × acerifolia*) and horse chestnut (*Aesculus hippocastanum*). These species were selected because they are among the most common urban species in central European cities and they represent different tree types (shade tolerant to light demanding, anisohydric to isohydric).

The module **climate** includes the monthly data of temperature, radiation, air humidity, wind speed, and precipitation.

In the module **plant development** the monthly leaf area, the leaf area index (LAI), and the monthly plant-specific factor for the potential evapotranspiration (f_{etp}) are calculated. Hereby, the maximum LAI of a tree species is computed on the basis of tree age using a polynomial

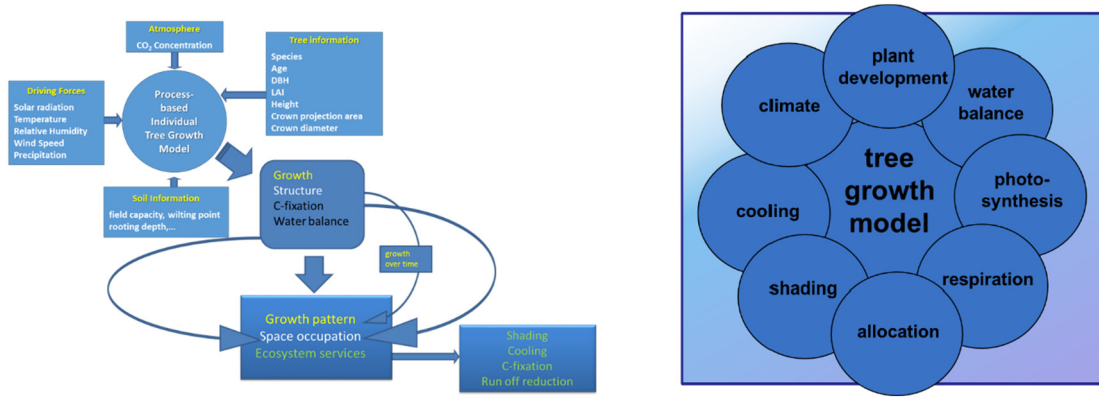


Fig. 1. Scheme and modules of the tree growth model CityTree.

function. These functions for the four tree species were derived from measurements in the six Central European major cities (see Chapter 2.2). Phenological observations specific for the urban region and the trees species denote start (bud break) and end (leaf coloring) of the growing season. In absence of phenological observations, long-term means of the phenological data (e.g. Chmielewski and Rötzer, 2001) can be used. Within the growing season LAI increases and decreases in a sinusoidal shape with a maximum in July. The total leaf area of a tree can be estimated by multiplying the LAI with the crown projection area CPA, which can be derived from the mean cd of a tree. The development of the plant-specific factor for the potential evapotranspiration f_{etp} is calculated in the same way as the monthly LAI, with species-specific maxima in July (Rötzer, 1996).

In the module **water balance** all parameters of a tree's water balance are calculated using the SVAT-model approach of HyMo (Rötzer et al., 2004). As initial values for the simulations field capacity, permanent wilting point and rooting depth as well as the soil sealing percentage must be given. The difference between field capacity and permanent wilting point defines the maximum plant available soil water content ψ_{max} . The central water balance equation can be defined as:

$$prec - int - et_a - ro - \Delta\psi = 0 \quad (1)$$

with $prec$ = precipitation [mm], int = interception [mm], et_a = actual evapotranspiration [mm], ro = runoff [mm], $\Delta\psi$ = change of the soil water content [mm].

With the exception of $prec$, all other parameters of Eq. (1) have to be calculated. According to the approach of the 3PG-model (Landsberg and Waring, 1997) the monthly amount of int is a function of leaf biomass, a tree's interception capacity and of the amount of $prec$:

$$int = f(LAI, int_{cap}, prec) \quad (2)$$

with LAI = leaf area index of the month [m^2/m^2], int_{cap} = species-specific interception capacity [mm].

The potential evapotranspiration et_p is calculated following Penman (e.g. Allen et al., 1998; DWA, 2018). The equation includes not only a temperature-humidity term and a ventilation term but also a radiation term. Consequently, the energy available for the evapotranspiration, as well as the transition of water into the atmosphere is described:

$$et_p = [s/(s + \gamma)] * (r_s - r_l)/L + [1 - s/(s + \gamma)] * e_s * f(v_u) \quad (3)$$

with γ : psychrometric constant in $hPa K^{-1}$; s : slope of the saturation vapour pressure curve in $hPa K^{-1}$; r_s : short wave radiation balance in $W m^{-2}$; r_l : long wave radiation balance in $W m^{-2}$; L : specific evaporation heat in $W m^{-2} mm^{-1} d$; e_s : saturation deficit in hPa ; $f(v_u)$: ventilation function with v_u being the daily average wind speed in $m s^{-1}$.

Et_p is the potential evapotranspiration of well-watered grassland. It can be transformed to the et_p of a tree species by using species-

specific factors $f_{etp}[t]$ based on Rötzer (1996, 2004). The monthly factors $f_{etp}[t]$ for $t = 1$ to 12 are calculated based on species-specific maximum values (see module plant development). Actual evapotranspiration et_a can then be derived from the potential evapotranspiration using $f_{etp}[t]$ and the reduction factor f_{red} :

$$et_a = f_{red} * f_p[t] * et_p \quad (4)$$

Hereby, f_{red} can be calculated as function of the plant available soil water content of the previous month ψ_v , the precipitation sum $prec$, the monthly sum of the tree's potential evapotranspiration $et_p[tree]$ and maximum plant available soil water content ψ_{max} :

$$f_{red} = (\psi_v - (et_p[tree] - prec)) / \psi_{max} \quad (5)$$

Assuming that stomata closure is depending on the CO_2 -concentration with the consequence of lower transpiration rates (Cassia et al., 2018) an increasing CO_2 -concentration of the atmosphere linearly reduces et_a by decreasing f_{red} .

Runoff ro is defined as the sum of surface runoff r_{surf} and percolation below the rooting depth:

$$ro = r_{surf} + per \quad (6)$$

Surface runoff r_{surf} is estimated as the percentage of sealed surface $ss\%$ multiplied with the amount of water reaching the surface:

$$r_{surf} = (prec - int) * ss\% / 100 \quad (7)$$

Percolation below the rooting depth occurs if the actual soil water content ψ_a exceeds the maximum soil water content ψ_{max} , with ψ_{max} is the difference of field capacity and permanent wilting point for the entire rooting zone:

$$per = \psi_a - \psi_{max} \text{ if } \psi_a > \psi_{max} \quad (8)$$

In addition, a hysteresis effect is included in the water balance module which considers soil remoistening depending on the previous drying out of the soil.

The water balance of a tree is linked with photosynthesis processes via stomatal closure. Stomata conductivity - estimated as a function of et_p and et_a and a species-specific scaling factor - reduces the internal CO_2 partial pressure p_{ci} in case of water shortage (Eqs. (11) and (12)).

The modules **photosynthesis** and **respiration** are closely linked. The calculation of net assimilation follows the method used a forest growth model (e.g. Rötzer et al., 2010) and is based on the approach of Haxeltine and Prentice (1996), i.e. information about air temperature, radiation, day length and CO_2 -concentration are required. We assume that 50% of the incoming short-wave radiation is photosynthetic active radiation (PAR). Using the LAI and a light extinction factor of 0.5 the

radiation amount of 1 m^2 leaf area can be estimated on based on an exponential function according to the Lambert-Beer law. This way, the gross assimilation per m^2 leaf area as daily mean of the month can be derived from:

$$A = d * [(J_p + J_r - \sqrt{(J_p + J_r)^2 - 4 * \theta * J_p * J_r})] / (2 * \theta) \quad (9)$$

with A: gross assimilation [$\text{g C m}^{-2} \text{ d}^{-1}$]; d: mean day length of the month [h]; J_p : reaction of photosynthesis on absorbed photosynthetic radiation [$\text{g C m}^{-2} \text{ h}^{-1}$]; J_r : rubisco limited rate of photosynthesis [$\text{g C m}^{-2} \text{ h}^{-1}$]; θ : form factor = 0.7.

J_p is defined as a function of the photosynthetic active radiation PAR in $\text{mol m}^{-2} \text{ h}^{-1}$ and the efficiency of carbon fixation per absorbed PAR [g C mol^{-1}].

$$J_p = c_p * \text{PAR} \quad (10)$$

Carbon fixation efficiency c_p can be estimated by:

$$c_p = \alpha * (p_{ci} - r) / (p_{ci} + r) * T * m_{\text{CO}_2} * i[t] \quad (11)$$

with α : intrinsic quantum efficiency for CO_2 uptake = 0.08 (C3 plants); p_{ci} : partial pressure of the internal CO_2 [Pa]; r: CO_2 compensation point [Pa]; T: species dependent adjustment function for tree age; m_{CO_2} : molecular mass of C = 12.0 g mol^{-1} ; $i[t]$: influence of temperature on efficiency.

The Rubisco limited rate of the photosynthesis J_r is further needed to calculate A:

$$J_r = V_m / d_{\text{max}} * (p_{ci} * r) / (p_{ci} + k_{\text{CO}_2}[t] * (1 + p_{\text{O}_2} / k_{\text{O}_2}[t])) \quad (12)$$

with V_m : maximum catalytic Rubisco capacity [g C m^{-2}]; d_{max} : maximum day length [h]; $k_{\text{CO}_2}[t]$: Michaelis Menten constant of CO_2 depending on temperature t [Pa]; $k_{\text{O}_2}[t]$: inhibition constant of O_2 against CO_2 depending on temperature t [Pa]; p_{O_2} : concentration of O_2 = 20,900 Pa.

Net assimilation A_N [$\text{g C m}^{-2} \text{ d}^{-1}$] can then be derived from the gross assimilation A and the dark respiration R_d by.

$$A_N = A - R_d \quad (13)$$

R_d of Eq. (13) is the product of the maximum catalytic Rubisco capacity and of β , the ratio of the maximum catalytic Rubisco capacity and the respiration costs (=0.015):

$$R_d = \beta * V_m \quad (14)$$

The maximum catalytic Rubisco capacity V_m - needed for Eqs. (12) and (14) - can be obtained by:

$$V_m = 1 / \beta * c_p / c_r * \text{PAR} * [(2\theta - 1) * \beta * d / d_{\text{max}} - (2\theta * \beta * d / d_{\text{max}} - c_r) * \varsigma] \quad (15)$$

Hereby, c_r and ς are defined by

$$c_r = (p_{ci} - r) / (p_{ci} + k_{\text{CO}_2}[t] * (1 + p_{\text{O}_2} / k_{\text{O}_2}[t])) \quad (16)$$

$$\varsigma = \sqrt{1 - (c_r - \beta * d / d_{\text{max}}) / (c_r - \theta * \beta * d / d_{\text{max}})} \quad (17)$$

The calculated net assimilation A_N based on the Eq. (13) represents the daily performance of a tree for the average day of a month. When multiplied by the number of days and the total leaf area the entire monthly net assimilation of the tree can be gained.

Within the module **respiration** the proportion of growth and maintenance respiration is quantified. We assume a fixed share of 50% as respiration based on the gross primary production (= A_N). The resulting net primary production NPP is transformed in content of fixed carbon

by multiplying the value with the carbon conversion factor which is assumed to be 0.5 (Yoon et al., 2013).

In the module **allocation** the annually gained carbon is divided up into the tree compartments, i.e., into roots, stem, branches and leaves. Further, a nonstructural carbon pool calculated based on age and the total biomass is assumed to meet respiration and defense demands.

Stem biomass is the product of stem volume and the specific wood density (Table S1). Hereby, stem volume until crown start is assumed to have a truncated cone shape whereby the radius of the stem base (0.2 m) is geometrically derived from the radius at breast height and h. Using species-specific correction functions, which were established based on measured terrestrial laser scans of urban lime and robinia trees, the modelled stem volume can be adjusted.

The volume of the stem within the crown is calculated as a cone using the radius at the crown start and cl as input. Branch biomass is estimated species-specific after Čihák et al. (2014), Annighöfer et al. (2012) and Patricio et al. (2005) as a constant fraction of the stem biomass for big trees and a dbh-dependent fraction for small trees. Because no data were found for plane trees we used the parameters of lime to calculate the branch biomass mass of plane. Foliage biomass is a function of leaf area and specific LAI (see Table 1). Stem-, branch- and foliage biomass together form the total aboveground biomass while total belowground biomass is the sum of fine root and coarse root biomass. Coarse root biomass is calculated following Cairns et al. (1997) as a function of the aboveground biomass and tree age. Initial fine root biomass is calculated as a constant fraction of the coarse root biomass (Table S1).

To allocate the carbon gained within a year into the tree compartments at first the nonstructural carbon pool has to be filled up based on the new total biomass (= initial total biomass plus NPP). Then, fine root biomass is calculated as a fixed fraction of the foliage biomass. The remaining carbon based on the total biomass represents the growth rate of the woody biomass. Using the above described procedures carbon is proportionally distributed to the branch and coarse root biomass. The new stem biomass is the sum of the initial stem biomass and the residual NPP. From the new biomasses the new dimensions of the trees, i.e. stem volume, cv, CPA, dbh and cd, as well as the new LAI can be derived. Hereby, we assume that the annual h increment of a tree i_H can be estimated by

$$i_H = a * \text{Age}^b - a * (\text{Age} + 1)^b \quad (18)$$

The factors a and b are species-specific values derived from regression analyses of measurements of lime, robinia, chestnut and plane trees in six Central European major cities (Table S1).

In the module **shading** the shaded area and the shade density is quantified. The shaded area is as a function of h and cd for the longest day of the year (June 21st):

$$A_s[h] = \cot(\delta) * h_t * cd_t \quad (19)$$

with $A_s[h]$: shaded area in m^2 for the hour h; δ : sun elevation angle of the day (=June 21st) for the hour h; h_t : tree height [m]; cd_t : crown diameter of the tree [m].

To depict a tree's mean daily shading area hourly values of the 21st of June between 8 am and 6 pm were averaged. The shade density is calculated based on the values of June and defined as leaf area per m^3 cv.

Within the module **cooling** the energy needed for the transition of water from liquid to gaseous phase (DWA, 2018) was calculated based on the CPA and the transpiration sum et_a :

$$E_A = et_a * \text{CPA} - (L_0 * -0.00242 * \text{temp}) / f_{\text{con}} \quad (20)$$

with E_A : energy released by a tree through transpiration [kWh tree^{-1}]; L_0 : energy needed for the transition of the 1 kg of water from the liquid

Table 1

Main characteristics of the six cities and long-term average temperature (temp.) and annual precipitation (prec.) for the period 1965–2015.

City	Population	Size [km ²]	Latitude [°]	Longitude [°]	Elevation [m]	Temp. [°C]	Prec. [mm]
Würzburg	126,010	87.6	49.79	9.95	177	9.6	599
Nuremberg	511,628	186.4	49.45	11.08	309	9.2	634
Hof	45,183	58	50.31	11.91	500	7.5	716
Bayreuth	73,065	66.9	49.95	11.57	340	8.4	728
Munich	1,464,301	310.7	48.14	11.58	519	9.6	960
Kempten	67,529	63.3	47.73	10.32	674	7.4	1257

to gaseous phase = $2.498 \text{ MJ (kgH}_2\text{O)}^{-1}$ and temp = temperature in °C; f_{con} : conversion factor (= 3.6 MJ/kWh).

2.2. Data for model development

Data from six Central European cities form the base for the development of the single urban tree growth model CityTree. The main characteristics of the cities as well as their climate are described in Table 1.

The largest city is Munich with >1.4 Mio. inhabitants and a size of app. 311 km^2 while Hof in the Northeast of Bavaria represents the smallest city with app. 45,000 inhabitants and a size of 45 km^2 . The mean annual temperature ranges between 7.4 °C in Kempten and 9.6 °C in Munich and Würzburg. The maximum mean annual precipitation sum was measured in Kempten with 1257 mm , the minimum mean annual precipitation sum can be found in Würzburg with 599 mm .

From very young trees with an age of 6 years up to old trees with an age of 210 years 2000 tree individuals of four species form the base for the model development (Table 2). Lime (*T. cordata*), robinia (*R. pseudoacacia*), plane (*P. × acerifolia*) and horse chestnut (*A. hippocastanum*) are the analyzed tree species all of which are the most common tree species in Central European cities (Roloff, 2016).

LAI was recorded for a smaller number of trees. The high variety of LAI values from 0.6 to 11.6 m^2 of leaf area per m^2 of surface area provide the basis for model development (see Moser et al., 2015).

2.3. Data for model validation

To validate the newly developed growth model CityTree, measurements of high spatial and temporal resolution from four sites in Munich (Pariser Platz, Bordeaux Platz, Edinburghplatz, Lehrer-Wirth-Straße) were available (Table S2). These datasets are completely independent from the data used for parametrization (see Chapter 2.2). The individual trees of all sites have a distance to other trees of >3 m. In some cases, crowns of the individual trees touch each other. Competition between the trees on the resources (water, nutrition, light), however, is small and can be neglected. The measured sap flow data were transformed to transpiration values, the aggregated to monthly amounts could then be compared to the simulated transpiration sums. Even though transpiration is only one validated parameter of the water balance, for physiological aspects it is the most important. A comparison of measured and simulated soil water contents would further improve the model quality.

The data set of the year 2015 originates from a study on growth and transpiration of lime trees at two squares in the center of Munich. The

two squares have strongly differing characteristics: While the Pariser Platz is a small circular square with a high degree of soil sealing, the Bordeaux Platz is an open square with a medium degree of soil sealing. For the simulation we assumed a soil sealing percentage of 90% for the Pariser Platz and of 80% for the Bordeaux Platz. The tree characteristics differed as well, particularly at the Pariser Platz. The other data set consists of measurements of lime (at Edinburghplatz) and robinia (at Lehrer-Wirth-Straße) for the year 2016 and 2017. The selected sites are located in suburban Munich (Trudering-Riem). The overall characteristics of both sites were similar, with low soil sealing percentages of 30% and open street/square conditions. For a more detailed description of the sites see Moser et al. (2016a), Rahman et al. (2017a, 2017b), Rahman et al. (2018) and Moser-Reischl et al. (2019).

At the four sites meteorological data (temperature, humidity, radiation, wind speed, precipitation) were recorded (see Rahman et al., 2017a, 2017b; Rahman et al., 2018), which form the driving forces of tree growth in the CityTree model for the validation of the simulations. The soil of the sites in the city center was estimated as loamy sand (field capacity: 18 vol%, permanent wilting point: 8 vol%) with a maximum rooting depth of 70 cm and the soil in the suburban sites as a sandy loam (field capacity: 25 vol%, permanent wilting point: 8 vol%) with a maximum rooting depth of 80 cm.

Dbh growth as well as monthly transpiration rates of individual trees were validated. Dbh increment was measured using stem radius growth precision dendrometers (Ecomatik, Dachau, Germany). The transpiration sum of an individual tree was estimated based on continuous sap flow measurements from June to October 2015 as well as from June 2016 to December 2017 using thermal dissipation probes (Ecomatik, Dachau, Germany) after Granier (1987). Both dendrometers and sap flow sensors were installed at a height of around 4 m from the ground to reduce vandalism. With visually derived sapwood depth from increment cores, the total sap flow was calculated and converted to the daily transpiration rate following Rahman et al. (2017a, 2017b).

2.4. Data base for the simulation study

For the model development as well as for the simulation study climate data from the six major cities were used (Table 1). Monthly values of temperature, relative humidity, global radiation, wind speed and precipitation formed the base of the simulations.

Climate scenario data for each city were derived from the regional climate model WettReg in which all climate parameters are statistically downscaled (Spekat et al., 2007). For our simulations for the near future the time series of the years 2016–2050 of the scenario A1B (Table 3)

Table 2

Number and morphological characteristics (mean, minimum and maximum) of the four measured tree species.

Parameter	<i>Tilia cordata</i>			<i>Robinia pseudoacacia</i>			<i>Platanus acerifolia</i>			<i>Aesculus hippocastanum</i>		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Number of trees	551			411			448			590		
Age [yrs]	44	11	140	40	6	102	38	4	160	68	14	210
dbh [cm]	32.9	6.4	107.0	39.7	6.0	102.2	37.1	3.9	158.7	50.1	6.5	123.6
Height [m]	13.0	5.0	32.0	14.5	5.0	29.6	15.7	6.0	32.0	14.4	4.4	30.0
Crown volume [m ³]	706	10	7265	874	7	5749	1760	15	18,025	1082	4	6257
Number of trees	348			305			168			175		
LAI [m ² /m ²]	3.7	0.7	8.4	3.7	0.6	11.6	2.4	0.9	5.4	3.0	0.7	5.8

Table 3

Annual average temperature and precipitation amount of the six major cities for the near future (2016–2050) under scenario A1B and difference of the values from the present climate (1965–2015).

City	Temperature [°C]		Precipitation [mm]	
	Average	Change	Average	Change
Würzburg	10.3	0.8	590	−9
Nürnberg	10.3	1.1	645	11
Hof	8.4	0.8	776	60
Bayreuth	9.1	0.8	759	31
München	10.2	0.6	959	−1
Kempten	8.5	1.1	1356	99

were used. The atmospheric CO₂-concentrations for this scenario are assumed to be 490 ppm on average for the period 2016–2050, while for the current climate (1965–2015) we use a mean CO₂-concentration of 390 ppm.

In the near future the annual mean temperature will increase between 0.6 °C in Munich and 1.1 °C in Kempten and Nuremberg. Simultaneously, the changes of the average annual precipitation will vary depending on the city. While it will be low in Würzburg (−9 mm) it will rise up to 99 mm in Kempten. However, in all cities the distribution of the precipitation over the year will change markedly. More winter precipitation will be associated with lower summer precipitation.

As soil characteristics are not known for the single sites we assumed for all simulation sites a sandy loam with a field capacity of 25 vol%, a permanent wilting point of 8 vol% and a maximum rooting depth of 100 cm, however, keeping in mind that the local soil conditions could vary considerably. For the simulations all calculations were done without soil sealing, i.e. a soil sealing of 0% was assumed.

For the simulation study we classified all measured trees (Table 2) into ten age classes and calculated the mean values of all required initial tree characteristics for the CityTree-model (Table S3).

3. Results

3.1. Validation of the urban tree growth model CityTree

3.1.1. Validation of growth module

Based on data sets which are independent from the data records used for model development, the behavior of the growth module was tested. The averaged, annual dbh increments of the two tree species at the four sites in Munich (Fig. S1) revealed no significant differences between measurement and simulation for lime at the Bordeaux Platz ($p > 0.50$) and at the Edinburghplatz ($p > 0.60$) as well as for robinia ($p > 0.80$) at the Lehrer-Wirth-Straße. At the Pariser Platz the measured

dbh increments were significantly different compared to the simulated ones ($p < 0.10$). The measured values were close to zero and partly below zero. However, a negative dbh increment is physiologically not possible and could therefore not be reproduced by a growth model. The reasons behind the negative values could be due to the markedly low water status of the trees at the Pariser Platz which lead to a shrinkage of the stem diameter (see e.g. Schäfer et al., 2018) and/or to an incorrect zero-point adjustment of the dendrometers for the year 2015. Therefore we excluded two trees with high negative dbh increments (< -0.2 mm) from the overall analyses (Fig. 2).

3.1.2. Validation of water balance module

To validate the water balance we used sap flow measurements and compared it to model results. Despite the fact that sap flow data provided hourly and daily transpiration values only monthly transpiration sums simulated by the model could be validated. The model CityTree was able to simulate the annual development of the monthly transpiration sums which are clearly site dependent and species-specific (Fig. S2). Despite some clear differences (e.g. lime at the Pariser Platz in July 2015) in most cases the simulations of the monthly transpiration sums are in good agreement with the measurements. On average, the differences between the simulated and measured transpiration sums of summer months (June–August) are smaller than 10%, the ones of the autumn months September and October are lower than 19%.

Taken together, the simulated values (species, years and sites) of the two validated parameters correspond well to the respective measurements (Fig. 2). The correlation coefficient between measured and simulated annual dbh increments of the 21 trees was 0.63. For the monthly transpiration sum the correlation coefficient was 0.92 showing obviously smaller deviations from the measurements.

3.2. Species dependent growth and dimensional changes of urban trees

Annual growth and ES of urban tree species were simulated for six Central European cities. The long-term mean of the annual dbh increment revealed clear differences between the cities (Fig. S3). In major cities with a low mean average annual temperature such as Kempten or Hof dbh increments were below 0.41 cm yr^{-1} for all species at an age of 50, while in Munich, i.e. in a city with a high mean average annual temperature and a high precipitation amount, highest increments up to 0.54 cm yr^{-1} for chestnut were calculated. Averaged over the cities, the annual dbh growth of 50-year old robinia and chestnut were with 0.47 cm and 0.40 cm clearly higher than the increments of lime (0.14 cm) or plane (0.30 cm).

While in all cities dbh growth of plane was the lowest, the total biomass of the plane trees increased stronger than the biomass of the other

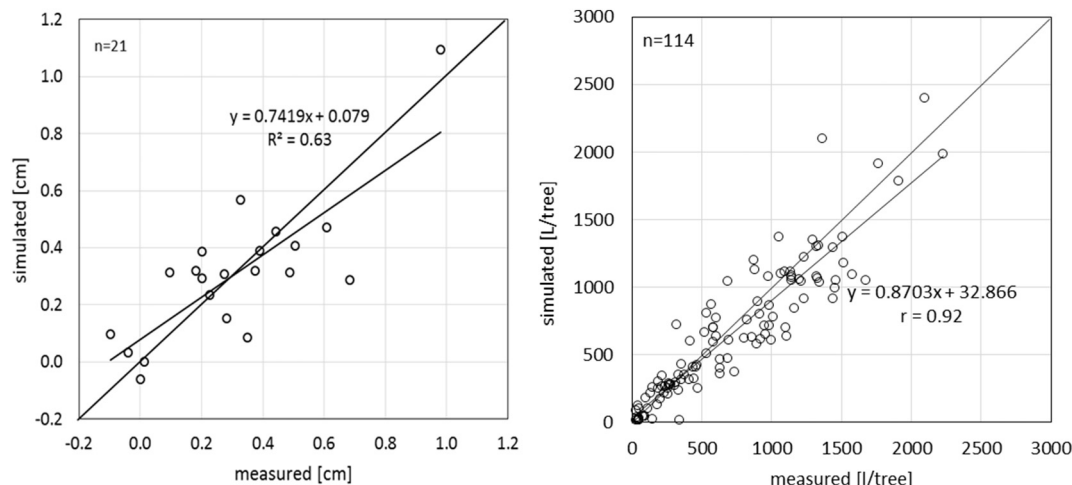


Fig. 2. Measured and simulated annual stem diameter increments (left) and monthly transpiration sums (right) of *T. cordata* and *R. pseudoacacia* at four sites in Munich.

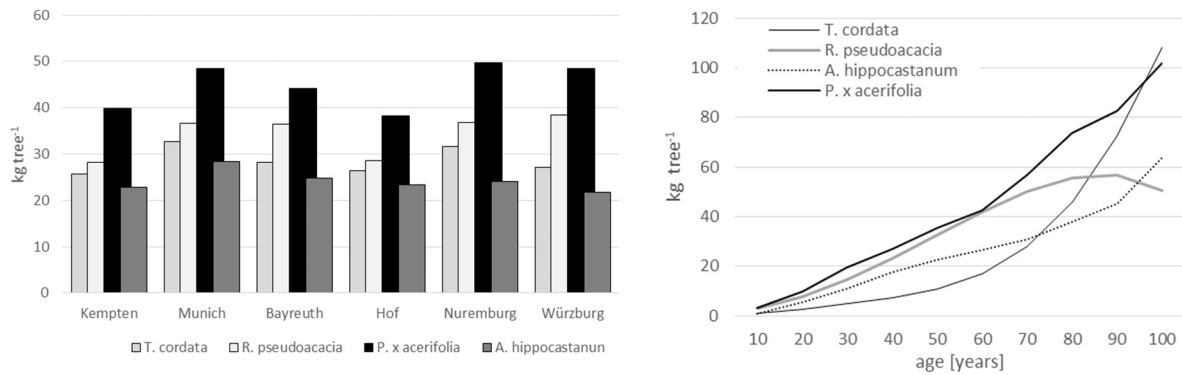


Fig. 3. Simulated total biomass increments (long-term averages for 1965–2015) for four tree species in six Central European major cities (left) and depending on tree age as means over the cities (right).

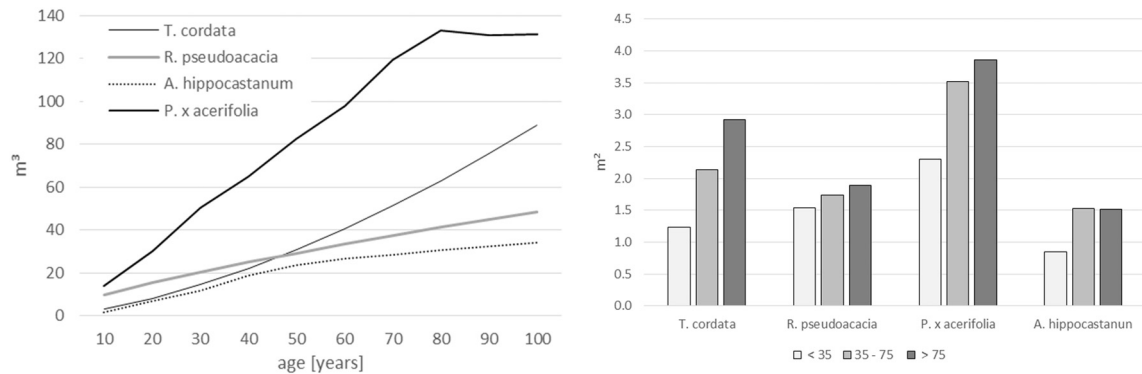


Fig. 4. Simulated annual mean increments (1965–2015) of the crown volume (left) and of the crown projection area (right) depending on tree age for the four species on average of the Central European cities.

species (Fig. 3). This is particularly true for trees older than 60 years. The maximum annual biomass increment was simulated for plane in Nuremberg with 50 kg. Lowest biomass increments were found in the “cold” cities of Kempten and Hof, where especially chestnuts have an annual biomass increment of only 23 kg. The biomass increments between species – averaged over the cities – all differ significantly ($p < 0.05$). Small mean annual biomass increments with values between 26 and 27 kg tree⁻¹ were also simulated for lime in Kempten, Hof and in the dry and warm city of Würzburg. With higher age, however, the increment of lime increased clearly.

Along with dbh and biomass increment tree dimensions change. However, the dimensional changes are only slightly dependent on site. Primarily, they are affected by species and age. In Fig. 4 the mean annual expansion of cv and CPA can be seen depending on species and age averaged by city.

An increase in cv and CPA with increasing age is obvious. The rate of the increase, however, depends strongly on the species (high for plane, low for chestnut). The largest annual increase of cv was registered for plane regardless of age. From an age of 75 years onwards the annual cv increase remained constant. All other species show clearly smaller annual increments of cv. A strong increase of the CPA is obvious for lime and plane of up to 3.9 m² per year. On the contrary, CPA of chestnut of medium-aged and old trees increased only by 1.5 m² per year.

3.3. Ecosystem services of urban tree species for Central European cities

Within this simulation study we analyzed the ES water consumption (=transpiration), shading, carbon fixation, runoff and cooling by transpiration of the four studied tree species in six Central European cities. The transpiration sum of a tree is closely linked with its growth. For all species, a steady increase with age is obvious. A 100-year old plane for

example, has a mean annual transpiration of 124 m³, which denotes the maximum of all simulated species (Fig. 5). The transpiration amounts of lime, robinia and chestnut is only within a small range up to an age of 50 years. The differences are between 1 m³ and 4 m³ for 10-year old trees and between 27 m³ and 29 m³ for 50 years old trees. For older trees, however, the differences between the species increased considerably (Fig. 5).

Shading is another important ES. The shaded area is dependent on the tree dimensions and thus on age (Fig. 6, left).

For all age classes, plane trees provide the largest shaded areas. A 100-year-old plane for example, shades an area of 571 m² on the 21st

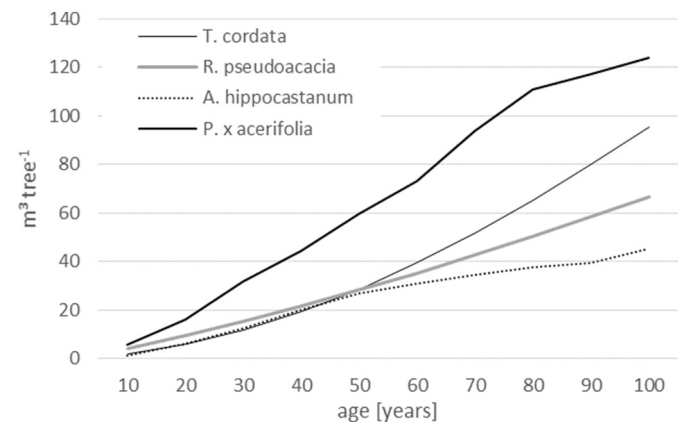


Fig. 5. Simulated mean annual transpiration amounts (1965–2015) of the four tree species on average of the Central European cities depending on tree age.

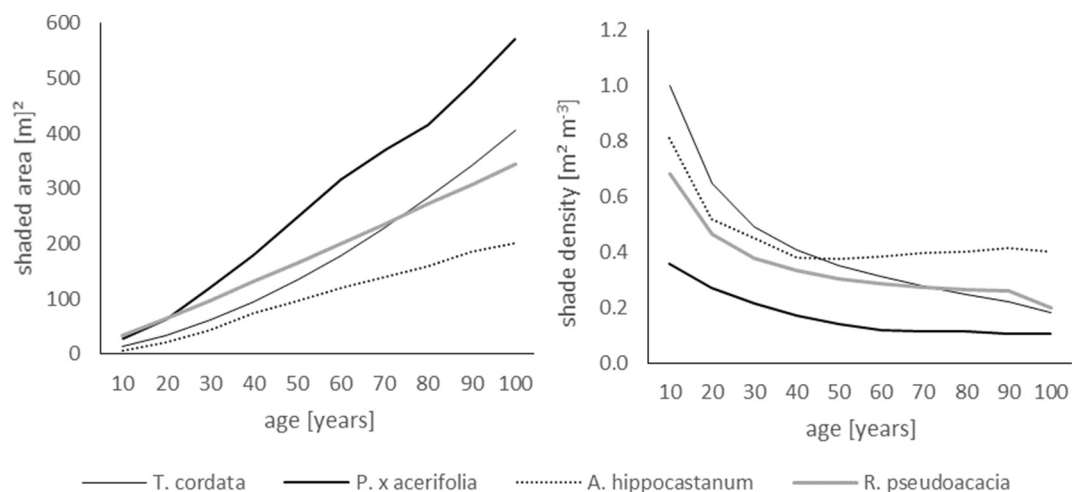


Fig. 6. Simulated shaded area (20th of June, 8 am to 6 pm, left) and shade density (June, right) for four species depending on tree age on average of the Central European cities.

of June while a chestnut tree of the same age shades an area of only 202 m². While trees increase their crowns with increasing age, the shading areas increase, the shade densities, however, decrease (Fig. 6, right). Besides lower canopy extension (Fig. 4), chestnut showed a more slender canopy growth which might lead to a higher shading density. With a higher percentage of canopy cover in a particular site, a higher shade density can increase the cooling effect.

The averages of the ecosystem services carbon fixation, water consumption, runoff and cooling by transpiration of the four tree species are summarized in Fig. 7.

Compared to the other species, significantly high carbon fixation amounts of 22.4 kg C tree⁻¹ were calculated for plane ($p < 0.01$, Fig. 7a). Clearly lower values were found for lime with 14.3 kg C tree⁻¹, robinia with 17.1 kg C tree⁻¹ and chestnut with 12.1 kg C tree⁻¹. The same pattern can be seen for the water consumption of the trees, i.e., their transpiration sums (Fig. 7b). A very high value of 65.3 m³ tree⁻¹ for plane, and clearly lower sums for the other species which were all below 36.3 m³ tree⁻¹.

Because runoff strongly varies with the amount of precipitation, we based the runoff for the different tree species on the mean of each city

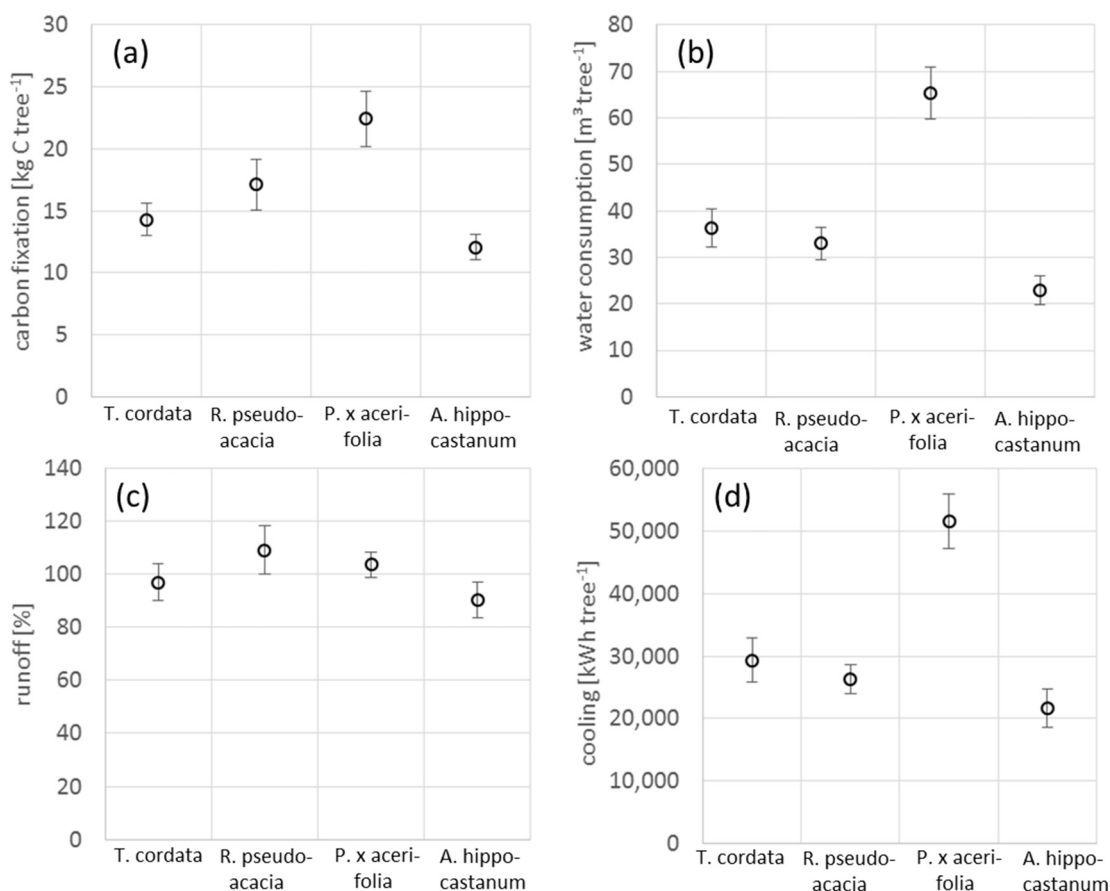


Fig. 7. Simulated long-term averages (1965–2015) of carbon fixation, water consumption, runoff (100% = mean runoff of all species for a city) and cooling by transpiration for four trees species on average in Central European major cities.

(Fig. 7c). We found that the runoff under robinia was for 9.1% higher than the averaged runoff for all species. In contrary, under chestnut the runoff was 9.7%. This means that the tree species-specific runoff amounts could vary for up to 18.8%.

Cooling by transpiration ranges between 51,649 kWh tree⁻¹ for plane and 21,675 kWh tree⁻¹ for chestnut (Fig. 7d). There were significant differences between all tree species ($p < 0.01$) except for lime and robinia which were only significant with $p < 0.1$.

3.4. Urban tree growth and ecosystem services under future climate conditions

The expected temperature increase with the changed precipitation patterns of climate scenario A1B along with a higher CO₂-concentration of the atmosphere will certainly affect urban tree growth and the provision of ES. On average for Central European cities the mean annual total biomass increments of the four trees species will rise in the near future (Fig. S4). The levels of the increment changes under future condition between the tree species are significantly different ($p < 0.01$).

Under the scenario A1B conditions of the period 2026–2050 the annual total biomass increment of robinia and plane increased for 26% and 24% compared to the long-term averages of the period 1965–2015. For chestnut the increase was only 19%. Differences between the cities range from 5% for robinia to 12% for chestnut.

Tree transpiration is strongly site and species dependent. In cities with high amounts of annual precipitation such as Kempten and Munich transpiration sums of all species increase under future climate conditions (Fig. S5). In contrast, in cities with low amounts of precipitation and a high mean annual temperature (Nuremberg and Würzburg) transpiration is reduced, particularly for plane. The highest increment was calculated with 7.8 m³ tree⁻¹ for plane in Hof.

Along with the growth rates, ES of the tree species will be altered under future climate conditions. Table 4 gives an overview of the percentage changes ($= (\text{value current climate} - \text{value future climate}) / \text{value current climate} * 100$) for carbon fixation, water consumption, runoff and cooling by transpiration depending on species and age.

The increment of the C-fixation for the four tree species varies between 13% for old chestnut trees and 17% for robinia trees under the conditions of the climate for the near future. The dependency on age is very low.

Water consumption, i.e. transpiration of robinia and plane will increase by 6% across age classes, while for medium and old aged lime and chestnut trees smaller amounts up to 6% can be expected.

The sums of precipitation and transpiration will affect the runoff below the trees. For medium aged and old limes and chestnuts the runoff amount will clearly increase between 12% and 20%. Independent of age only small increases of 3% were calculated for robinia and plane.

Regardless of age, an increase of the cooling by transpiration of 5% for robinia and plane is obvious under near future climate conditions. In contrast, medium aged and old trees of the other two species show

a reduction of the cooling in Central European cities, while young trees show only a very small reaction.

4. Discussion

In most eco-physiological models plant growth is controlled by photosynthesis (source control). For this purpose the C-assimilation by photosynthesis is estimated depending on its main drivers CO₂, light, temperature, nutrients and water supply (Fatichi et al., 2014). Tree growth is indirectly estimated based on the amount of carbon assimilates minus losses by respiration (Hayat et al., 2017). However, the current understanding (Körner, 2003; Körner, 2013) is that growth is directly depending on temperature, nutrients and water (Fatichi et al., 2014) and that photosynthesis is controlled by growth (sink control). So, direct control of growth (carbon sink) by environmental conditions is more important than the indirect control by photosynthesis; the direct environmental control of growth becomes mostly limiting before photosynthesis is controlled. If water or nutrients are limiting growth, photosynthesis can be down-regulated, as carbon is sufficiently available and not the growth limiting factor. This fundamental change in the hierarchy between growth and photosynthesis explains that tree growth is accelerated by rising atmospheric CO₂-concentration, i.e. impaired by carbohydrates but not limited by temperature, mineral nutrients or water. In order to integrate this change of understanding in models, growth should be directly controlled by environment as in classical dendrometric models (Pretzsch et al., 2007) with a feedback to photosynthesis in order to activate or down-regulate depending on the mode of growth limitation. In the model CityTree this approach was realised by the regulation of the stomata for CO₂-uptake and water release which is controlled by both the CO₂-concentration and the water availability.

4.1. Plausibility of simulation results and usage of urban tree growth models like CityTree

Using data for transpiration and dbh increment of individual trees from different sites of a Central European major city (Munich) we could show that the urban tree growth model CityTree is able to realistically simulate single tree growth and a tree's water balance.

With coefficients of correlation $c_{\text{cor}} = 0.92$ for the measured and simulated annual transpiration amounts the values are in a similar range Rötzer et al. (2017) obtained when comparing water balance measurements with simulated data (volumetric soil water content) of individual beech trees ($c_{\text{cor}} > 0.8$) by using the complex forest growth model BALANCE. The significant differences in the species-specific transpiration amounts we found for lime, robinia, chestnut and plane trees (Figs. 5 and 10) have also been reported by Konarska et al. (2016) for the city of Gothenburg/Sweden including the species *T. europaea* and *A. hippocastanum*, by Pataki et al. (2011b) for Los Angeles/USA, by Peters et al. (2010) for the suburban areas of Minneapolis/St.Paul/USA

Table 4

Change [in %, $= (\text{value future climate} - \text{value current climate}) / \text{value current climate} * 100$] of ecosystem services for four trees species in Central European major cities for the near future (scenario A1B - 2026–2050) compared to the present climate (1965–2015).

Ecosystem service	Age class	<i>T. cordata</i>	<i>R. pseudoacacia</i>	<i>A. hippocastanum</i>	<i>P. × acerifolia</i>
C-fixation	<35 years	16	17	16	16
	35–75 years	16	17	14	16
	>75 years	16	17	13	16
Water consumption	<35 years	3	6	2	6
	35–75 years	−1	6	−6	6
	>75 years	−2	6	−4	6
Runoff	<35 years	6	3	9	3
	35–75 years	12	3	20	3
	>75 years	13	3	18	3
Cooling by transpiration	<35 years	2	5	1	5
	35–75 years	−2	5	−5	5
	>75 years	−2	5	−4	5

and by Chen et al. (2011) for the city of Dalian/China. For August the transpiration amount of plane was 5487 l H₂O per tree in the urban area of Los Angeles (Pataki et al., 2011b). Our simulations revealed for the same month and for trees of the same size (dbh = 57 cm) an e_t sum of 7201 l H₂O per tree by using average Central European climate conditions. Given that the water availability is much better under Central European conditions the results of the CityTree model appear to be sound and realistic.

With correlation coefficients of 0.76 for tree growth, the annual dbh increment of the urban tree species lime and robinia were simulated quite realistically. Taking into account that dbh increment increases sharply from seedlings to young trees but is constant or decreases after reaching maturity (Assmann, 1961; Pretzsch et al., 2017) the simulated values of the model CityTree and the values from literature (Moser et al., 2016b; Dahlhausen et al., 2016; Gillner, 2012) suit well in the course of dbh growth within the lifetime of trees.

When comparing three tree genera, the highest annual dbh increments were obtained for the genus *Robinia* followed by *Platanus* and *Tilia* (Bühler et al., 2007). Thus, the dbh increments for tree species simulated by using the model CityTree match well to the measured increments found in literature for Central European cities when the age of the tree is taken into account.

Stand biomass and biomass increments of individual trees cannot be measured directly. They must be derived from primary measurements. By using allometric equations which are in most cases based on dbh and h measurements, C-storage and biomass of individual or of single tree compartments can be estimated (Aguaron and McPherson, 2012; Yoon et al., 2013; Timilsina et al., 2014). However, such equations are limited for the species and to the regions and the time period for which they are developed. Thus, estimating tree growth for regions with distinctly different site conditions and/or under clearly changed climate conditions like for future climate scenarios can produce misleading results. Further, often equations based on forest tree data are used to calculate biomass and growth of urban trees, because measurements of urban trees are rare (Aguaron and McPherson, 2012). This might lead to false results. To overcome these shortcomings process-based growth models are appropriate tools. By using the model CityTree a process-based calculation of the growth and ES of four important urban tree species is possible. Limitations of the model CityTree are that currently the model is parametrized for only four tree species, that the nutrient supply of the trees is not yet considered, and that – despite the simplifications in some calculations – the extent of the input variables is still high and cannot be determined for all sites. A further limitation is that so far the model can in one simulation run estimate the growth and ES of only one tree. However, these topic will be solved the next development step of the model CityTree.

4.2. Growth and ecosystem services of urban tree species in Central European cities

4.2.1. Tree growth and dimensional changes

The simulation results show that growth and dimensional changes of trees vary distinctly in Central European cities depending on species, age and environmental conditions such as climate or soil characteristics. Species-specific differences in growth and dimensions are consequences of the behavior of trees towards light, temperature, nutrients and water. Contrasting ecological strategies of species to regulate the internal water flows by stomatal response, i.e. isohydric versus anisohydric behavior (McDowell et al., 2008) may result in changed growth rates under stress (Moser et al., 2016a). Isohydric species such as robinia or plane close their stomata immediately during limited water availability while anisohydric species like lime show a less sensitive stomata regulation. A closing of the stomata, however, is accompanied by reduced photosynthesis, i.e. lower biomass increments. Indicators for the growth reaction of trees on the water availability are the drought tolerance and the water demands of the species.

Niinemets and Valladares (2006) and Roloff (2013) describe robinia as a very drought tolerant species with a very low water demand, while plane is described as highly drought tolerant and medium water-demanding. When comparing the simulation results of the cities of Munich and Würzburg which have the same mean annual temperature but contrasting amounts of precipitation (Munich: 960 mm, Würzburg: 599 mm) the species-specific strategies are obvious (Fig. 3, left). The two isohydric species exhibit equal biomass increments in both cities (plane) or even higher biomass increments in the dry city (robinia). In contrast, the anisohydric species lime reveals a 20% higher growth rate in the wet city of Munich, and chestnut – a medium water-demanding species with a low drought tolerance (Niinemets and Valladares, 2006; Roloff, 2013) – has 31% higher growth rate in the wet city.

Along with the influence of climate and tree species, age alters the biomass growth rates and the structural development. The simulations of the biomass increment and the tree dimensions over age follow the universal representation of the net productivity development (e.g. Lyr et al., 1992) if the species-specific life times of the trees are taken into account.

All results of the present study area based on the soil type sandy loam with a maximum rooting depth of 100 cm and a soil sealing percentage 0%. However, it is often reported that the soil and surface parameters can influence the water balance of a tree and thereby alter growth to a great extent. Urban trees e.g. are strongly affected by limited rooting space (Bühler et al., 2007), poor accessibility to soil water (Morgenroth and Buchan, 2009), or restrictions based on impervious surfaces (Rahman et al., 2013). The model CityTree is able to simulate tree growth and ES based on different input parameters such as varying percentages of surface sealing and/or different soil types with different rooting depths. Fig. 8 depicts the model's representation of the effect of changed maximum plant available soil water contents on the biomass increment of the different species in relation to the soil type sandy loam (=1).

It is apparent that the maximum plant available soil water and the species-specific water demand modify the biomass increment, particularly for species with a high water demand like chestnut.

4.2.2. Transpiration and runoff

Along with a tree's transpiration and interception rates and on the basis of the soil characteristics the entire water balance of a single tree in the course of a year can be calculated by the urban tree growth model CityTree. The simulations of age-dependent transpiration sums of the species are within plausible ranges and have been validated against measurements. High differences in the amount of transpiration

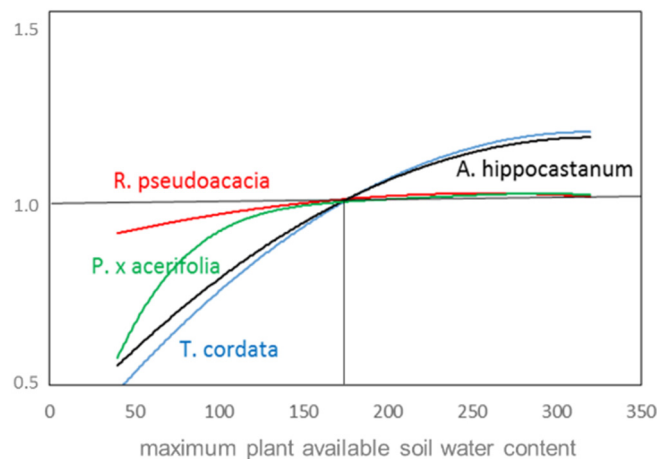


Fig. 8. Relative change of the simulated mean annual biomass increment of the four tree species (age = 60 years) depending on the maximum plant available soil water content on average in Central European major cities (reference = sandy loam).

between are obvious, with plane showing the highest values ($65 \text{ m}^3 \text{ yr}^{-1}$) and chestnut the lowest values ($23 \text{ m}^3 \text{ yr}^{-1}$) both calculated for medium-aged trees (50–60 years old). Peters et al. (2010) found similar differences in the annual transpiration of six genera for the temperate climate in the suburban landscapes of Minneapolis and St. Paul/Minnesota. For *T. americana* trees with a dbh of 22.8 cm on a loamy soil type for example, they reported an annual transpiration rate of $6.8 \text{ m}^3 \text{ yr}^{-1}$. For the city of Hof which has nearly the same amount of precipitation and the same mean annual temperature we simulated a transpiration of 6 to $8 \text{ m}^3 \text{ yr}^{-1}$ for lime (dbh = 20 cm) growing on loamy sand with surface sealing percentages between 50% and 0%. Summing up, trees can consume huge amounts of water by transpiration and interception, which reduces runoff and cools the environment. The quantity strongly depends on tree characteristics (species, dimension, age) and on the soil and climate conditions.

Vegetation is able to intercept water from rainfall, store it in the plant canopy from where it can be evaporated. In addition, plants can take up water from the soil. This way, runoff can be reduced and the risk of floods can be minimised (Ennos et al., 2014). The model CityTree is able to simulate surface runoff and percolation below the rooting zone depending on the species, the tree dimensions and on soil characteristics and climate. The influence of tree species on the total runoff varies between -10% (chestnut) to $+9\%$ (robinia), i.e. on average for Central European cities tree species can change the runoff up to 19%. In individual cities the alterations can be much larger. For Munich a maximum runoff difference with 40% of all six cities was simulated. Studies of Armson et al. (2013) and Ennos et al. (2014) show that on asphalt surfaces up to 60% of the rainwater drained off directly, while vegetation reduced runoff almost completely.

4.2.3. Cooling by transpiration

Our simulations showed that cooling by transpiration depends to a great extent on age and species and is modified by the site conditions. Previous research found that characteristics of species such as tree morphological characteristics including shape, canopy size, canopy density as well as leaf features can influence the overall tree cooling effect (Kong et al., 2016; Rahman et al., 2015; Smithers et al., 2018). However, the effect of transpirational cooling to tree features is more complex since not only the morphology which governs the cooling but also physiological processes play a significant role along with the atmospheric demand (Rahman et al., 2017a). Tree morphological characteristics (Table 2) and biomass increment (Fig. 3) of the selected species also followed the water consumption rate in the present study. Moreover, diffuse porous, anisohydric species such as lime and plane also showed higher transpiration rate compared to the ring porous robinia and diffuse to almost semi-ring porous, isohydric chestnut. At the same time, with similar air temperature at the two cities Würzburg and Munich but with higher amount of precipitation in Munich, the transpiration rate from Munich was higher. Thus, the simulation results are in line with the experimental findings that higher atmospheric demand drives higher transpirational cooling if soil water availability is not limited. Consequently, Jacobs et al. (2015) showed lower mean evapotranspirational cooling rates over a four month period by mature parkland trees in Rotterdam, Netherlands of $21\text{--}28 \text{ W m}^{-2}$, though maximum cooling was up to 200 W m^{-2} just after rain. Long-term transpirational cooling as simulated in the current study ranges between 21,675 and 51,649 kWh tree $^{-1}$ (Fig. 7d) and can be translated as 59 and 75 W m^{-2} which is close to the value reported by the experimental study in Munich of 82 W m^{-2} in July 2015 (Rahman et al., 2017a).

4.2.4. Shading

For the cooling of an urban square or street, i.e. for decreasing the temperature below a tree canopy shading plays an important role (Kong et al., 2017). Under the shade of trees Rahman et al. (2017b) or Coutts et al. (2016) for example found up to 1°C (for Munich) and 0.9°C (for Melbourne/Australia) lower temperatures when compared to

the surrounding open area. Tree morphological characteristics like canopy size and density, crown shape or leaf characteristics are responsible for the degree of cooling through shading (Rahman et al., 2018). Among the parameters of different species, LAI is considered as a central parameter affecting light penetration and below canopy microclimate (Kong et al., 2017; Lin and Lin, 2010). We used two indicators to describe the quantity of shading by trees species. One is the shading area that is determined by the tree dimensions, the other the canopy density which is based on the leaf area per cv, i.e., a function of the LAI.

Our simulations show that the shaded area increases, while the shading density decreases with increasing tree age. Both shade indices vary clearly between the species. Plane for example has for all age classes high shade density indices while the shaded area of chestnut is the lowest for all age classes of the four studied tree species. The strong age and species dependency we simulated for Central European cities was also found by McPherson et al. (2018) for the US. They further noted that the shade factor, i.e., the tree crown percentage covered by foliage and branches, was clearly higher for young trees (dbh < 30 cm), regionally different and non-linear which can also be seen in the results of our study. We agree with the conclusions of McPherson et al. (2018) that not only one single shade factor should be used for a tree species but rather tree age and regionally adapted values.

4.3. Urban tree growth and ecosystem services under future climate conditions

The future climate of our major cities will be modified markedly both by global climate change and by urban climate modifications, i.e. through increasing urbanization with reduced wind circulations, changed water balances and radiation patterns and an increasing UHI-effect (Rötzer, 2007; Ossenbrügge and Bechtel, 2010; Armson et al., 2013; Rahman et al., 2017a, 2017b; Pongracz et al., 2010). It is still unclear how urban trees respond to these changes and how ES provided by the urban trees will be affected. In the last century tree growth in metropolises was accelerated worldwide and further enhanced in the city center compared to the rural surroundings (Pretzsch et al., 2017). Way and Oren (2010) found that dbh and biomass growth increased under enhanced temperature levels and was stronger for deciduous tree species compared to evergreen species. The simulations of the current study resulted in a species-specific increase of the biomass of 22% on average over all cities for the near future with an average temperature increase of 0.9°C and 1.1°C and an increase of the mean annual precipitation sum of 32 mm per year. In addition to the changed climate also the higher CO_2 -concentration of the atmosphere might be responsible for the enhanced tree growth. Pretzsch et al. (2017) reported that increased temperatures, changes in the precipitation patterns, higher CO_2 -concentration but also fertilization through higher N-depositions and extended growing seasons are the drivers of accelerated tree growth. We could reproduce these relationships for the first three factors by using the model CityTree.

However, a further increase of the temperature above the species-specific thermal limits and longer lasting, more intensive and a rising number of extreme events like droughts can cause negative effects on tree growth (e.g. Nitschke et al., 2017; Bialecki et al., 2018). Water stress is a crucial factor that is able to reduce urban tree growth (Meineke and Frank, 2018). Meineke and Frank (2018) report that at high and mid latitudes, photosynthesis and growth is enhanced by increasing temperatures as long as the water supply for trees is not restricted and temperature values are below their thermal limits (Way and Oren, 2010; Chung et al., 2013). In our simulations tree species under climate change revealed lower transpiration rates in cities where water supply is already limited under current conditions (Fig. S5) as well as for older lime and chestnut trees (Table 4). Cooling by transpiration displays the same patterns, i.e., reductions for old lime and chestnut trees and in cities with high average annual temperatures and low

precipitation amounts under current climate conditions (e.g. Nuremberg and Würzburg). This is crucial because especially in dry and warm cities a high transpirational cooling potential of trees is beneficial to moderate the high temperatures of a site (Massetti et al., 2019; Yu and Hien, 2006; Rahman et al., 2019a). Massetti et al., 2019 pointed out that urban trees can alleviate the thermal stress of humans in cities, in particular under warm conditions. And Rahman et al. (2019b) demonstrated that the effects of urban trees on the microclimate by transpiration are strongly species-specific, e.g. the transpiration and hence cooling potential of lime was three times greater than the transpiration rate of robinia. Therefore, the right choice of tree species could be decisive to mitigate the climate of a square or a street in a city, especially in view of future worsened conditions in cities (Coburn, 2009; Gill et al., 2013; Savi et al., 2015). Compared to medium aged chestnut, our results showed that plane trees of the same age class have an on average 10% higher cooling potential under near future climate conditions in the six Central European cities. Moreover, the runoff under these two medium-aged tree species differs by 17%, i.e., in the near future under chestnut trees runoff increased by 20%, under plane only by 3%. Therefore, along with the information on growth, vitality and resilience of trees under future climate change (Niinemets and Valladares, 2006; Roloff et al., 2008; Meineke and Frank, 2018) the influence on their ES should be taken into consideration when planning climate adapted cities. Not only tree species and tree age but also micro-climatic conditions have huge influence on services such as carbon fixation, water consumption, runoff, shading or cooling by transpiration. Therefore, urban trees are a feasible option to adapt cities to a changed future climate and mitigate climate change in urban surroundings (Shashua-Bar et al., 2010; Zhang et al., 2018).

5. Conclusions

The newly developed growth model CityTree is one of very few models that simulate tree growth in urban surroundings and that are simultaneously able to project future tree growth and ecosystem services. In a first simulation study we gave a brief insight into potential applications of such a model. Compared to other urban focused tree growth models such as i-Tee, CityGreen or UrbTree, which all can be categorized as empirical models, CityTree is process based. Consequently, physiological equations form the main calculations of tree growth. Thus, biomass increment is calculated from the environmental conditions such as climate or soil characteristics. This makes the model unique, as climate and water balance driven tree growth can be simulated for small scale environmental changes as well as for large scale changes. The linkage of tree growth with ecosystem services such as water consumption, carbon fixation or cooling by transpiration is a further exceptional component of the model.

Simulated growth and ecosystem services such as carbon sequestration and cooling by transpiration of four tree species included in this study differed greatly and were species dependent. This has important implications for urban forestry that aims to maximize the benefits obtained from trees for increasing sustainability and adaptation of urban areas to climate change.

These simulations, however, are strongly biased by the specific stand climate and the overall climate of the city which can vary immensely due to geographical influences. In particular water supply is decisive for urban tree growth. Therefore, tree species such as lime, which have a limited capacity to control transpiration, showed great variation in their growth performance and ecosystem services. Robinia, on the other hand, is able to resist water shortage via stomata closure. While this behavior leads to reduced growth and hence limited transpirational cooling during drought periods which are expected to become more frequent and prolonged under climate change, it assures the long-term growth of the species.

Currently we prepare a manual based on CityTree simulations that shows in figures and tables growth patterns, dimensional changes and

ecosystem services of different tree species for Central European cities under present and future climate conditions. This manual can support city planners, architects, landscape planners, scientists and landscapers, etc. to mitigate climate change and the urban heat island effect and may adapt cities to expected new climate conditions as well as to other environmental changes like increasing soil sealing or intensified overbuilding.

CityTree is a single tree growth model. Therefore, the model is currently not yet able to simulate interactions, growth and corresponding ecosystem services at the stand level. Extending the model to other tree species, broadening the range of ecosystem services and developing approaches for scaling will be three main challenges for our future work.

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Author's contributions

T.R. designed and developed the model and wrote the paper, M.R. and A.R. contributed to data collection and data preparation as well as to writing the manuscript. H.P. and S.P. contributed to writing and revised the entire manuscript.

Competing interests

The authors declare that they have no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.04.235>.

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